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Implications of energy policy on a product system's dynamic life-cycle environmental impact: Survey and model

Jun-Ki Choi*, Paul Friley[1], Thomas Alfstad

Sustainable Energy Technologies Department, Brookhaven National Laboratory, Upton, NY 11973, USA

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Successfully developing and manufacturing industrial products requires considering the economic- and environmental-factors that span multiple spatial- and temporal-scales. Here, we propose an integrated approach combining an energy-economic model with a life-cycle assessment to analyze the impacts of energy policies on the dynamic changes in the various environmental impacts of a product system. We employ the Market Allocation (MARKAL) framework to foresee the changes in several economic- and technological-parameters over specific periods for different energy policies. Furthermore, we create a dynamic life-cycle inventory database to assess the changes in the future life-cycle environmental impact of a current product/process system. Our proposed method may guide industry to proactively prepare for the possible effects of different energy policies on their current product/process system's environmental profile so that they can make strategic decisions on modifications to, and investments in their production processes thereby to enhance their environmental- and economic-performance while meeting the various emission-abatement targets.

Contents

1. Introduction

Integrating environmental aspects into corporate social responsibility (CSR) and management strategy has become a fundamental factor driving producers towards choosing technologies with low environmental impact while maintaining their products economic feasibility [1]. New energy standards, such as ISO 50001, require industries to commit to efficient usage of energy in their production process and supply-chain management while meeting their goal of abating emissions [2]. In addition to these voluntary actions, different energy policies, such as carbon taxes and cap-and-trade, directly and indirectly affect the supply and demand of energy commodities. While there are many different tools for modeling

* Corresponding author. Tel.: +1 631 344 2723; fax: +1 631 344 3957.
E-mail addresses: jkchoi@bnl.gov (J.-K. Choi), pfriley@bnl.gov (P. Friley), t.alfstad@iaea.org (T. Alfstad).
[1] Tel.: +1 202 646 5206.

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energy economy, most methods for assessing technology and analyzing policy tend to focus on the macroeconomic-scale levels. However, for making strategic management decisions, manufacturers need methods and tools to assess the effects of energy- and environmental-policies at the value-chain level. Industries are interested in addressing two questions: How will the environmental- and the economic-performances of current product/process systems be changed with potential future energy policies? Which part of the process should be enhanced to meet, at the minimum cost, the required emission-reduction target of the energy policies?

Although some energy economic models, such as the Market Allocation (MARKAL) offer information about anthropogenic emissions generated by the economic activities, they often lack sufficient detail to allocate the information to each part of a product's life cycle. Life cycle analysis (LCA) can provide information about a product's environmental features of most interest based on the past/current life cycle inventory database. However, general LCA is a static accounting model, rather than an optimization model. It usually does not support either the systematic evaluations of the impacts of substituting technologies on a medium- or a long-term basis, or the cost effectiveness and market competition of alternative choices. Therefore, it is difficult to model the prospective change in environmental impacts of a product/process system caused by the changes in various potential federal/state-level energy policies and environmental regulations. In this paper, we integrate the strengths of both approaches to create a dynamic lifecycle inventory database that is applicable for analyzing the changes in the future lifecycle environmental impact of a current product/process system under a set of alternate energy/environmental policies. In Section 2, we review existing energy economic models, various life-cycle analyses, and previous studies on combined models. In Section 3, we explain our proposed methodology using the case study of the Photovoltaic dynamic LCA. Section 4 illustrates the results of the proposed methodology that will afford guidance for industrial designers in foreseeing the impact of certain macro-economic energy policies and environmental regulations on their decision-making during the process of developing the product.

2. Literature reviews

2.1. Energy-economy modeling tools

Extensive research on modeling the relationship between the economy and environment has focused specifically on the relationship between the economy and the energy system. Energy-economy models can be categorized into *top-down* and *bottom-up* models [3]. The former evaluate the system from aggregate economic variables, and concentrate on the economic description of interactions and relations between aggregate economic systems. Therefore, they cannot detail the behavior of the energy system. These top-down approaches can be classified further into input–output models, econometric models, partial equilibrium- and computable general-equilibrium (CGE) ones [4–6]. Bottom-up models utilize detailed information about different technologies, and relate energy consumption or supply to technical performance. The limitation of this approach is that it usually neglects feedback effects from the economy. The bottom-up approaches are classified into dynamic optimizations and dynamic simulation-models [7–12]. They utilize dynamic linear- and nonlinear-optimization for energy supply and demand systems. To overcome the weakness of both the bottom-up model and the top-down model, a *hybrid model* also was formulated by combining the two approaches, such as MARKAL-MACRO [13].

Among the many choices of energy-planning models, we selected Market Allocation (MARKAL) for assessing our proposed methodology. It is a technology- rich energy systems analysis approach to evaluate the long-term impacts of environmental- and policy-decisions on the cost-effective deployment of advanced technologies and resources. It identifies the optimal developmental pathway for an energy system over time under given technology characteristics and boundary conditions. More than 100 institutions in 70 countries around the world have used it to analyze a wide array of issues, such as environmental policy, energy policy, subsidy- and tax-regimes, efficacy of R&D programs and their associated benefits, assessment of energy-efficiency programs, and energy-market forecasts [14]. The first version of MARKAL model was developed in the late seventies at Brookhaven National Laboratory New York in collaboration under the auspices of the International Energy Agency's Energy Technology and Systems Analysis Program (ETSAP) and United States Department of Energy. Since then, the model has been bettered continuously and validated by the user community. It computes energy balances at all levels of an energy system: Primary resources, secondary fuels, final energy, and energy services. The function of the model is to identify energy services at minimum global cost by simultaneously making decisions on investments in equipment and on operating decisions and primary energy supply. The model selects that combination of energy technologies that minimize the total cost of the energy system over the projected period [15].

2.2. Life cycle analysis

Life cycle analysis (LCA) is the most widely accepted process for identifying and evaluating the environmental performance of a product over its entire lifetime, i.e., extraction of raw material, its processing, manufacturing, distribution, product use, and end-of-life management. It is a popular approach for analyzing the "cradle-to-grave" consumption of resources and emissions of industrial products and processes [16,17].

Generally, LCAs can be categorized based on the source of the life cycle inventory (LCI) data, and the set-up of the system's boundaries: Bottom-up- and top-down-approaches. The former approach relies on detailed inventory of the inputs and emissions of selected processes [18]. These data usually represent average industrial numbers for a selected geographical region and manufacturing process. Therefore, it is called as process LCA. However, using an often arbitrary boundary can introduce significant errors into the LCA results [19,20], so constituting a major obstacle in the wider use of process LCA. An alternative approach is an economic input–output LCA (EIO-LCA). In this top-down approach, the flows typically are quantified in monetary terms and the flow between economic sectors of a region is determined. An important advantage of the latter is that it considers the entire economy and, unlike the process LCA, avoids defining an arbitrary boundary around selected processes [21]. However, data representing each sector must be tightly aggregated to maintain computational tractability. Hybrid analysis compromises the weakness of both the process LCA and the EIO-LCA [22]. In addition, there is an extensive version of EIO-LCA, viz., the Ecological LCA (ECO-LCA) that encompasses the contribution of natural capital to economic input–output models so to capture the analyses at the ecosystem scale [23,24]. Some researchers prospectively discussed the approach to analyze the consequence of changes in marginal energy-technologies [25,26]. However, most of these tools usually do not consider directly the environmental impacts caused by changes in energy policies and potential technological progresses, such as their efficiency, the introduction of new technologies, and retirement of old ones.

2.3. Combined approach

A combination of both MARKAL and LCA is promising because it will incorporate the strength of both methods. Some previous

studies addressed the importance of integrating both approaches. Material flows were introduced in the MARKAL framework to optimize the energy- and materials systems for CO_2 emissions [27–30]. These studies were intended to analyze the relationship of the material production- and consumption-system to the energy system and the integral emissions of greenhouse gases caused by changing the materials' life cycles, such as by materials substitution, increased materials efficiency, and recycling. There also are studies internalizing external costs into partial equilibrium models, such as MARKAL, to identify the best paths for implementing technological innovations and strategies for sustainable energy supply and use [31–33]. In these methodologies, economic- and environmental-parameters are fed into the MARKAL model that supports the consideration of additional aspects, such as restricted availability of the resource, or learning curves. However, to our best knowledge, this is a dearth of tools for analyzing the dynamic environmental impact of a certain policy on the life cycle of a product system level. Therefore, we propose a general framework for undertaking a multi-scale predictive LCA (MP-LCA) of a product system by combining these two tools.

3. Methodology

Fig. 1 illustrates the general framework of the Multiscale Predictive (MP) LCA and summarizes the steps. First, various carbon mitigation policies are considered in the energy-economy model—MARKAL.

Running MARKAL enables modelers to identify a cost-effective energy portfolio and to evaluate the effects of different energy/environmental policies, such as, among others, carbon taxes, cap and trade policies, and, clean energy standards. MARKAL generates dynamic outputs, such as changes in the electricity-generation mix and the carbon intensity of technologies for future years resulting from altering various economic- and technological-parameters (i.e., energy prices, technology learning, retirement, and efficiency improvements) over the selected timeframe for different policy schemes.

Since the electricity generation technologies categorized in the MARKAL are much detailed than those available in the current life cycle inventory (LCI) database, its output is aggregated by using input resources allocated to LCI database. For examples, the U.S. MRM database includes many different coal-steam generation technologies based on the type of coal and its sulfur content used as the input fuel, and the technology's characteristics. These technologies are aggregated as "coal steam" and they are further aggregated as "coal" together with Integrated Gasification Combined Cycle (IGCC), and the IGCC with carbon capture. Similar aggregations are applied to other conventional electricity-conversion technologies. As an example of renewable generations, around 10 different wind-technologies are classified in the U.S. MRM based on the resource's class and location (i.e., onshore vs. offshore); these technologies are amassed under Wind for the electricity-conversion technology for the LCI.

The focus of the LCA side is to create the dynamic LCI for a product/process system. After forming the static LCI for a

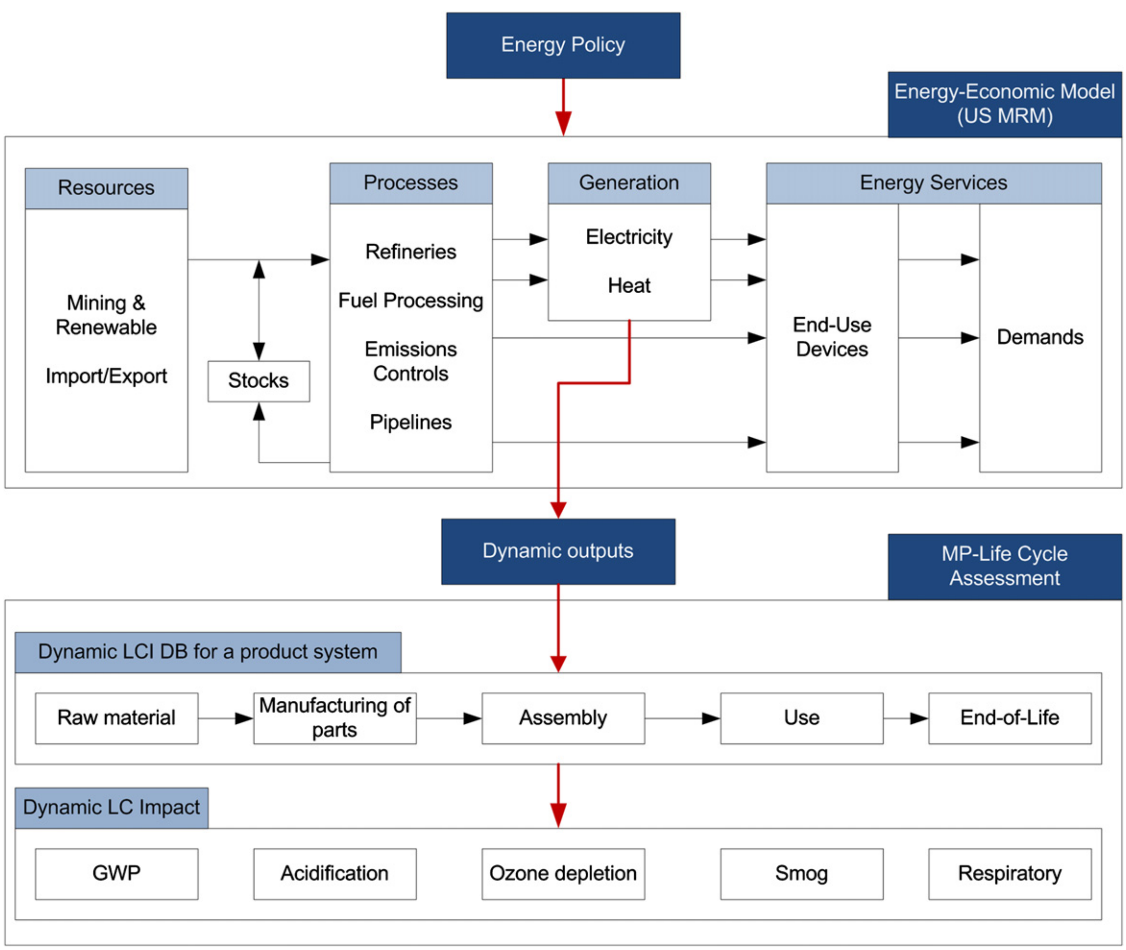


Fig. 1. Framework for MP-LCA for a production system.

system is formed, the average electricity used for each stage of the product's life cycle therein is disaggregated with respect to the information on percentage electricity-generation mix gathered from MARKAL for each period and policy. Thereafter, the change in emission intensities for fossil-fuel-based electricity generation over this time is considered to create a dynamic LCI database for a product's life cycle. For example, the total LCI of CO_2 emission from a product's lifecycle can be broken down into the emission generated from producing electricity and the emission from all other production processes in each step of product's lifecycle. Furthermore, the emissions from producing electricity can be subdivided into the direct emissions from burning fossil fuels, and the indirect ones associated with the other activities, such as the transporting fuels and the mining resources in the upstream process. As an example, U.S. LCI states that 93.3% of the CO_2 is the direct emission for average U.S. electricity generated from burning bituminous coal; the rest is indirect emissions. After breaking down the emissions into direct and indirect ratios, the change in the carbon intensity of each electricity conversion technology is further multiplied by the direct emission part so to account for the effect of various economic- and technological-parameters caused by different energy policies.

Eq. (1.1) is a generalized equation used to calculate the total amount of life-cycle environmental impact for each period and policy.

$$\varepsilon_{il} = \left\{ \sum_j \sum_k [\alpha_{ij}\gamma_{ijk} + (1-\alpha_{ij})]\mathrm{LCI}_{ijk} + \mathrm{LCI}_{ipk} \right\} \delta_{kl} \tag{1.1}$$

i=year; j=electricity-generation technologies; k=associated emission related to each impact category (i.e., CO_2, CH_4, N_2O…); l=environmental impact categories (i.e., GWP…); ε_{il}=total environmental impact of a product for each l in year i; LCI_{ijk}=life-cycle inventory of emission k for electricity generation j in year i; LCI_{ipk}=total life-cycle inventory of emission k from other processes in year i; α_{ij}=fraction of direct emission from j in year i (indirect=1-alpha); γ_{ijk}=emission intensity of k for j in year i (i.e., carbon intensity); δ_{kl}=life cycle impact weighting factor l for emission k (i.e., TRACI)

Among many measures of impact assessment, we applied “Tool for the Reduction and Assessment of Chemical and other Environmental Impact” (TRACI) 2.0. TRACI 2.0 is a life-cycle impact-assessment tool developed by the U.S. Environmental Protection Agency's (EPA)'s National Risk Management Research Laboratory [34]. It supports the quantification of potential environmental effects, such as ozone depletion, global warming, acidification, smog formation, effects related to human-health criteria, ecotoxicity, and fossil-fuel depletion. TRACI 2.0 is considered to be the best applicable tool to studies of the North America cases because the inventory's database is gathered from public sources from the U.S. government agencies, such as the U.S. EPA, U.S. Department of Agriculture, and U.S. Department of Energy [35].

4. Case study and results

4.1. Energy policies

BNL's Multi-Region U.S. MARKAL model (U.S. MRM) is a 10-region model of the U.S. energy system designed using the MARKAL framework. The main source of the technological assumptions therein is the Energy Information Administration (EIA) where much of the relevant information is published annually as part of the Annual Energy Outlook (AEO) [36] and the associated National Energy Modeling System (NEMS) documentation [37–48]. Other information was gathered from surveys of residential-, commercial- and manufacturing-energy consumption [49–51], the annual coal, natural gas and petroleum annual reports [52–56], the refinery capacity report [57] and the electric generator database [58]. The U.S. MRM reference case includes federal- and state-energy policies and regulations currently enacted by law. However, the convention is not to make any assumptions about future actions by lawmakers. Policies currently set to expire, but that traditionally have been extended every few years (e.g., the production tax credits for renewable electricity generation) therefore are allowed to expire in the reference case. Beside this, three different carbon-policies are analyzed: The Clean Energy Standard (CES), which is a requirement that a certain share of the electricity sold comes from energy sources, such as renewable-, nuclear- and CCS- (carbon capture and sequestration) ones; Cap and Trade (CO2CAP); and, a \$100/tCO_2 Carbon Tax (C100).

4.2. Electricity-generation mix

Fig. 2 is MARKAL output of the electricity-generation mix by running four policy cases. The percentage mix of each generation technology for each period is used for disaggregating the aggregated average electricity consumed throughout the lifecycle of PV (i.e., the existing LCI informs us that 110kwh medium voltage of electricity is employed to produce 1 kg of poly-silicon; we assumed that this amount is generated from various technologies with the percentage mix shown in Fig. 2). Although the mix varies for different regions in the United States, we adopted the national average mix, assuming that at each life-cycle stage of PV the same mix is employed. We feel that this is a reasonable assumption since the U.S. LCI is based on the national average.

As is evident from Fig. 2, in the base-case scenario (reference), the United States continues to rely on the relatively cheap fossil-fuel-fired electricity-generation technologies, since there are no carbon-reduction policies. Therefore, in our reference case, about 65% of electricity still is expected to be derived from these traditional technologies in the year 2050 in our reference case. For all other cases of carbon mitigation-policy, it is evident that using fossil fuels for producing electricity will decrease significantly and will be replaced by nuclear- and renewable-sources. For the C100 case, the use of natural gas for generating electricity keeps increasing through 2030, even with a tax of \$100 per ton of carbon. Growth constrains on installing new nuclear- and renewable-generation capacity leads to a rise production by existing gas-fired generation systems, so to replace more carbon-intensive coal-fired generation. By 2030, sufficient new nuclear- and renewable-generation capacity could be installed and the usage of gas-fired generation start to fall.

4.3. Carbon intensity

Fig. 3 shows the example of the change in average carbon intensity (kg CO_2/kW h) for coal- fired electricity generation resulted from running MARKAL. The carbon intensity of coal-fired generation changes with the introduction of new, more efficient coal-fired generation capacity, as it does with the incorporation of carbon-emission reduction technologies, such as CCS, in the alternative policy cases. For example, the red line in Fig. 3 indicates the C100 case, wherein the carbon intensity of coal-fired electricity generation drops significantly over time, even though the carbon price remains constant in real terms. This effect is due to constraints in building new coal-fired power plants with CCS. This information is used for creating a dynamic LCI of electricity generation, and is fed into the life-cycle analysis of a PV technology.

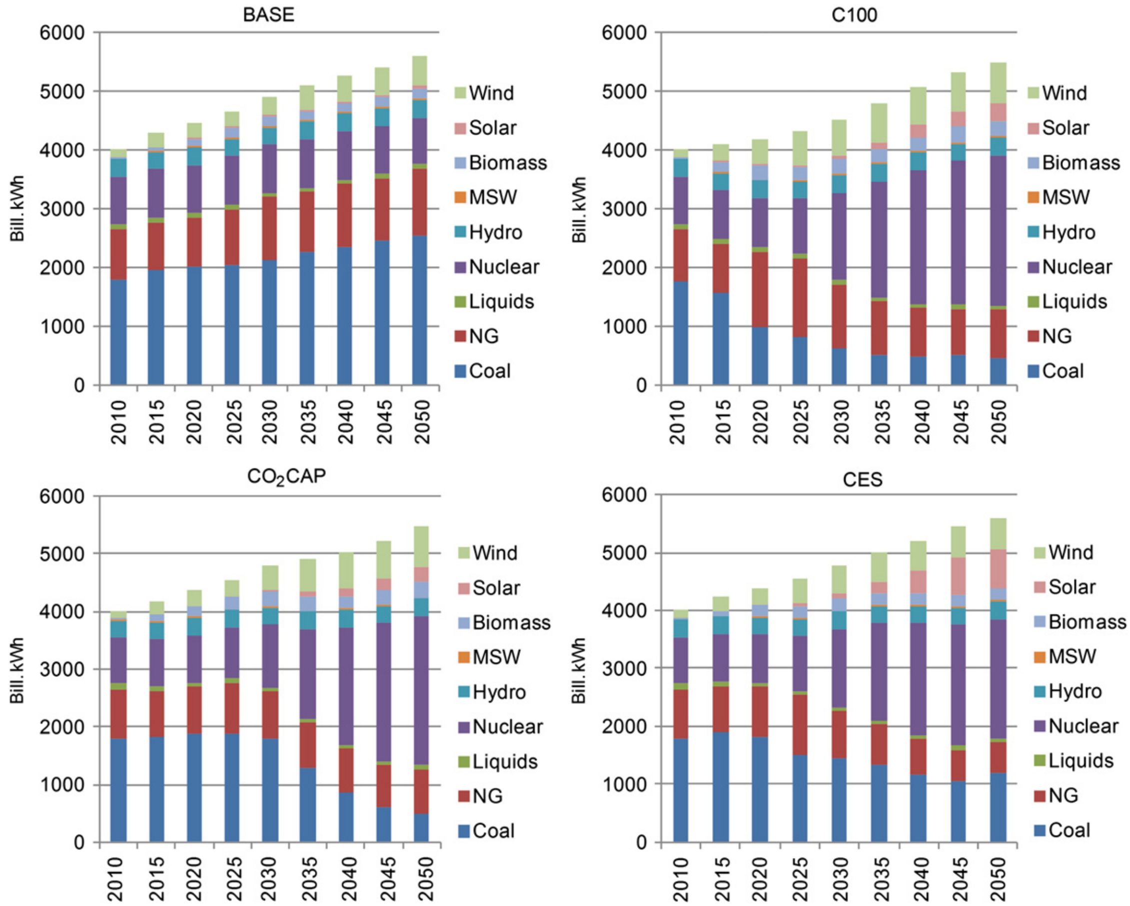


Fig. 2. Electricity generation from different input resource for four different cases.

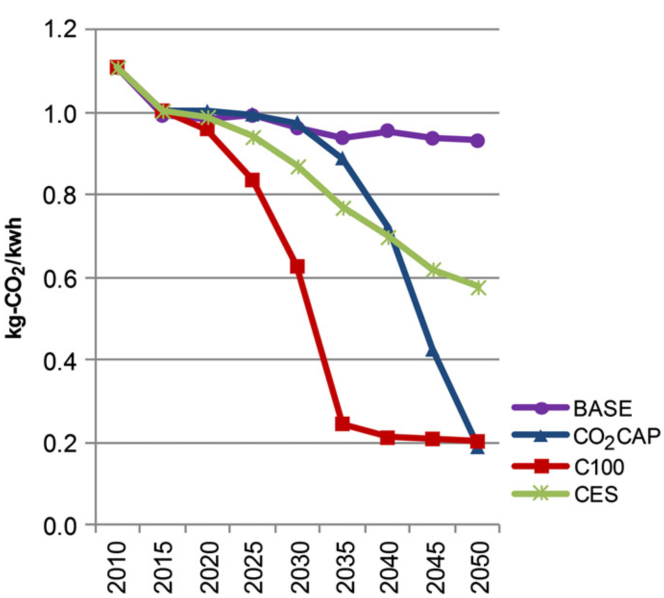


Fig. 3. Change of carbon intensity from coal-fired electricity generation for four different policy scenarios.

4.4. Dynamic photovoltaic lifecycle inventory

From the LCA side, we considered the cradle-to-gate LCA of a crystalline silicon photovoltaic. Numerous studies have detailed the life-cycle impacts for PV technologies. Most studies compare GHG emissions, cumulative energy demands (CEDs), and energy payback times (EPBTs) of different PV technologies in a static manner (i.e., static period time/snapshot). This kind of analysis serves well in comparing different technologies, although there are criticisms since the results from different studies differ significantly. To this end, recent studies [59,60] harmonized the life-cycle GHG emissions from PVs to reduce variability on the reported numbers. Rather than focusing on comparing different PV technologies, we adopted one of the publically available LCIs on crystalline-silicon PV technology [61], and modified it to the United States case using the U.S. LCI database compiled by the U.S. National Renewable Energy Laboratory (NREL) [62]. This database individually accounts for gate-to-gate, cradle-to-gate, and cradle-to-grave associated energy- and material-flows into and out of the environment in producing a material, component, or assembly in the United States. Although, in our study we adopted most of the LCI database from U.S. LCI, we tried to apply the most appropriate ecoinvent database [63] for processes where the U.S. LCI is not available. The LCA example we used for the case study is a cradle-to-gate analysis since it does not include the usage phase nor the end-of-life phase of the PV lifecycle. In establishing our system boundaries, we targeted the aspects that would concern a producer of integrated PV whose business model encompasses the production of poly-silicon, wafers, and cells, and the assembly of modules. Therefore, we did not include the LCI of the Balance of System (BOS) components that typically comprise the structure for mounting the PV arrays or modules, and the power-conditioning equipment that adjusts and converts the DC electricity to an AC load. The environmental profile of the BOS mainly reflects the indirect impact due to the production of materials for the mounting structures, such as steel, concrete, and aluminum. In addition, we did not include the recycling of PV

module; some PV manufacturers are interested in the recycling of their module, so then the end-of-life LCI can be incorporated in the analysis [64,65].

4.5. Dynamic lifecycle environmental impacts of PV

Fig. 4 illustrates the change of various environmental impacts per module production for four different policies. Acidification is the increasing concentration of hydrogen ions within the local environment that may damage to building materials and other structures, pollute lakes, streams, and rivers, and poison various plants and animals. Sulfur dioxide and nitrogen oxides from burning fossil fuels have been the largest contributors to acidification [66]. As shown in Fig. 4a, each of the three policy cases predicts a drop in acidification for the PV life-cycle. Although the model's sensitivity to each policy scenario differs, the retirement of coal-fired generation plants contribute to the declining profiles of acidification. Furthermore, much of the remaining coal-fired generation is IGCC with CCS. This effect is strongest for the carbon-tax scenario (C100). Fig. 4b illustrates the change of Global Warming Potential (GWP) that follows a similar trend as acidification. Again, the major decrease in GWP is due to the lessening generation of electricity from coal and gas, and the associated decline in upstream processes, such as coal mining and natural-gas extraction. Additionally, the decreasing carbon intensity of the coal-fired plants contributes to this result. While the increment is not significant, Fig. 4c shows that the level of ozone-depletion derived from the life cycle of PV module increases under the policy cases relative to the reference case. Ironically, this can be explained by the increasing market penetration of PV under these policies. This impact is due to the usage of chlorofluorocarbons (CFCs), trichloromethane, chlorine, and sodium

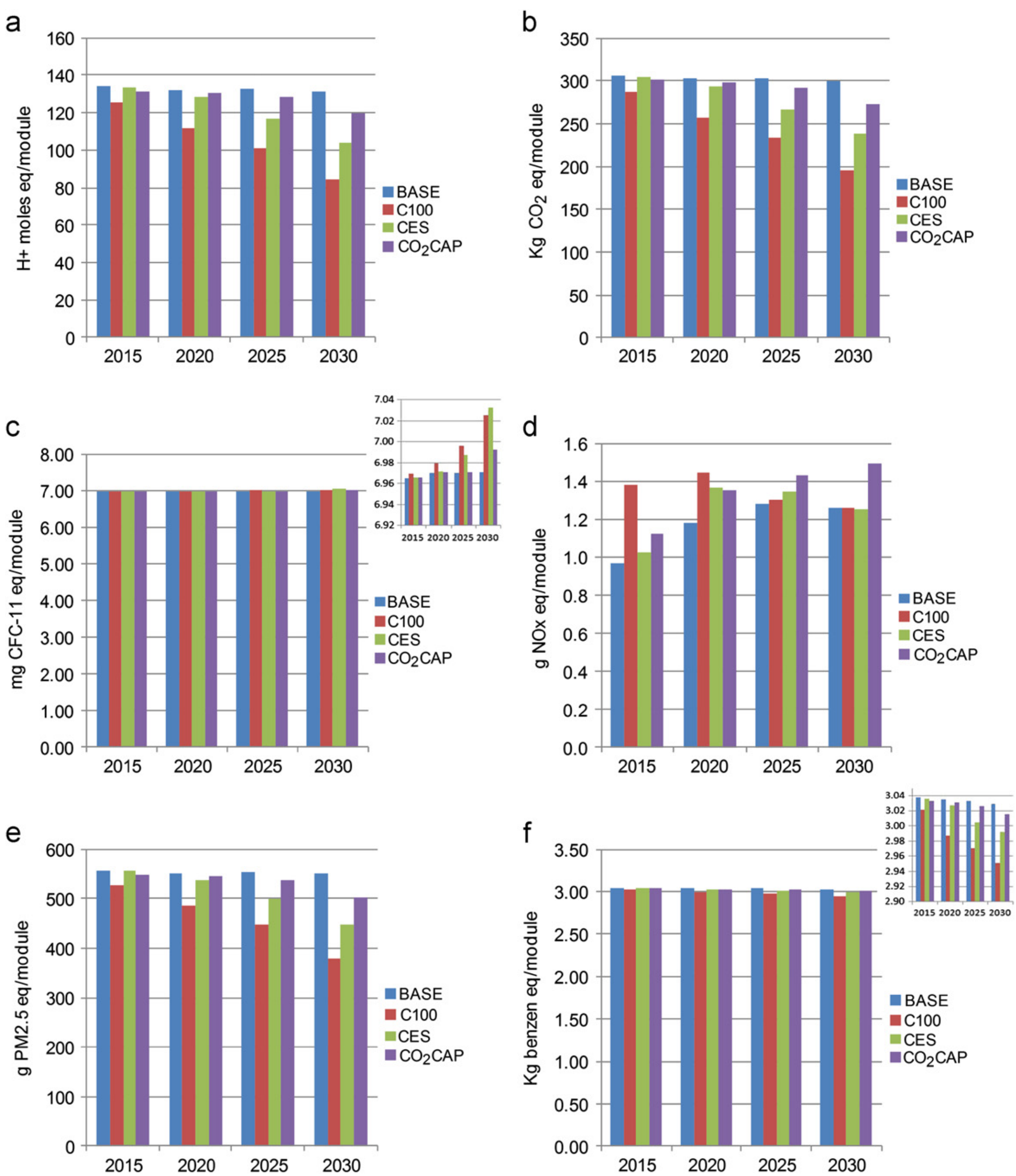


Fig. 4. Environmental impacts of PV for four different policy scenarios. (a) Acidification, (b) GWP, (c) Ozone depletion, (d) Smog, (d) Respiratory effect and (f) Carcinogenics.

hydroxide in PV manufacturing. Thus, as the alternative carbon policies provide an incentive for increased market penetration of PVs, more CFCs will be generated from manufacturing PV modules. We also see an increase in smog-forming emissions under these alternate carbon policies. A key contributor to the smog is NOx emissions [35] from biomass- and fossil fuel-electric generation. Although the former rises over time in all cases, the three carbon-mitigation policy scenarios predict have higher growth in biomass generation than does the reference case. Therefore, the carbon mitigation scenarios have higher NOx emissions, along with the resulting increase in smog formation. Fig. 4d shows the changes in smog over the years. Some respiratory illnesses and death originated from inhaling particulate matter, which is a collection of small particles in ambient air. Such matter may be emitted as particulates, or may be the product of chemical reactions in the air. As shown in Fig. 4e, particulate emissions decline in the carbon-mitigation scenarios relative to the reference case. The reduction in emissions of PM2.5-eq for PV manufacture primarily reflects the reduction in coal-fired generation. As depicted in Fig. 4f, there are minor declines in benzene emissions due to the lessening of coal-fired electricity generation. Some other impact categories in TRACI are related to negative human-health effects, such as non-carcinogenic illnesses, and eco-toxicity. Since these environmental impacts shown in Fig. 4 have some trade-offs among different policy scenarios, this information may be useful to industrial product/process design teams for prioritizing their strategic decision-making processes.

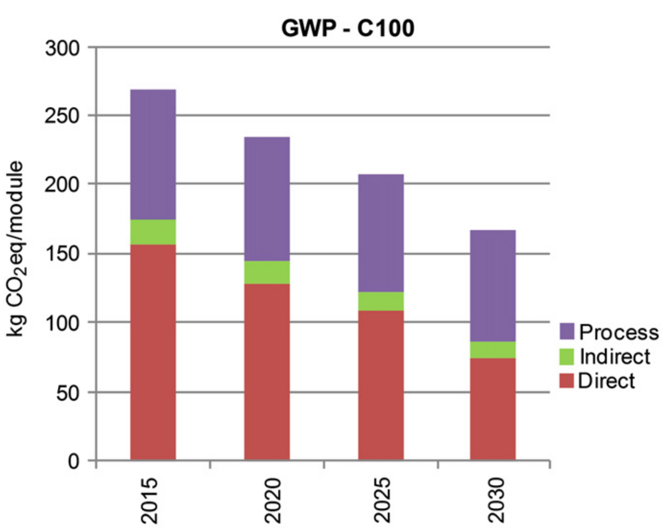


Fig. 5. Breakdown of the total GWP for life cycle of PV by source.

4.6. Environmental issues in manufacturing PV modules

The findings from life-cycle analyses can be interpreted in different ways; Fig. 5 illustrates the breakdown of the change of total GWP in the year 2020 for the case of the C100 policy. Direct emissions includes those from burning fossil fuel (coal, natural gas, oil) for generating electricity; indirect emissions represent the transportation of materials and the infrastructure for constructing electricity-generation utilities. Process emission includes every other source of emissions emanating from the PV-manufacturing process, other than electricity use. This graph illustrates the result of a hypothetical energy-efficient production process targeting a 5% decrease of electricity use in every 5 years for manufacturing one PV module. Major decreases in global-warming potential resulted from not only reducing the use of electricity in the PV production process, but also from the increasing cleanliness of the generation mix due to the carbon-tax policy. Accordingly, Industry may use this type of analysis to evaluate the amount of necessary investment for meeting the targeting goal of abating greenhouse gases.

We can further break down the emissions by process, and identify the major prospective environmental issues for each life-cycle stage of PV from the MP-LCA. Fig. 6 illustrates the 2020 prospective GWP- and smog-impacts for each stage of the PV manufacturing process. Here, the poly-silicon production stages are the largest contributors to these impacts because they require large amounts of energy for coke reduction, distillation, and Siemens process where the polycrystalline silicon is grown at very high temperatures. Simens process requires hydrogen and produces more hydrogen-cloride as a by-product. Wafer production includes some energy intensive processes such as Czochralski process for the production of a cylindrical shaped ingot and wafer cutting with a diamond saw. Therefore, bettering the energy efficiency of the poly-silicon production could be given the highest priority and designers may come up with a short list of options for such improvement. If designers think that the improvements in efficiency for poly-silicon production lines is saturated, then they can look for the next highest priority process to enhance the environmental profile of the total life cycle of the PV production. This information could afford options for selecting the design for the environment (DfE) strategies for product

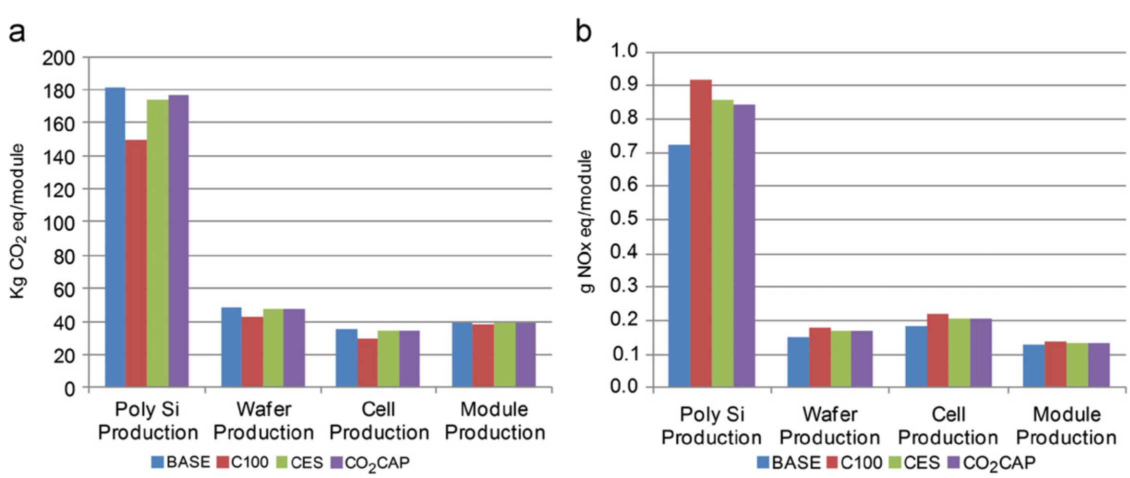


Fig. 6. GWP and smog impacts of PV lifecycle stages. (a) GWP-2020 and (b) Smog-2020.

designers and engineers to consider in upgrading the environmental performance of their future product-development process throughout all the stages of the lifecycle s(i.e., raw material extraction, manufacturing, distribution, use, and end-of-life management) [67,68].

5. Conclusion

Our study addresses the relationship between energy policy and the environmental lifecycle of a product system. We demonstrated the dynamic impact of various carbon-mitigation policies in terms of the environmental impacts of a product and interpreted the results to identify the major environmental problems in a product's life cycle. The industrial sector long has been the United State's largest energy consumer, currently representing about 33% of the total energy consumption. Therefore, spurring efficient energy consumption in the industrial sector is very crucial in meeting the challenges of climate change. Both policy makers and industrial managers, respectively, need to understand the impact of an energy policy on the environmental profile of industrial processes so they can prepare effective energy policies and assure strategic corporate-management decisions. As a last comment, while we considered the potential changes in the quality of the production recipe (i.e., quality of energy used) due to different energy policies, we have not analyzed the impact of changes in the quantity of the production recipe (i.e., fixed amount of energy, materials, chemicals used for the PV production). Considering such impacts is the logical next step in this methodology and will be the focus of our future work.

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